Investigation of the Mean Flow in a Complex Multi-Connected Estuary: South Puget Sound

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Abstract
We use the South Puget Sound Area Synthesis Model (SPASM), based on the Environmental Fluid Dynamics Code (EFDC), to explain and quantify seasonal changes in the mean flow across more than 20 transects in the basin. We derive the volume transport of water across many more transects in South Puget Sound than has been done before. The mean flow is derived from a moving 709-hour window applied to model output. We compare modeled transports to historical current meter measurements, where available.

Model results suggest: (1) tidal prisms are a poor way to estimate flushing times in southern Puget Sound; (2) calculated mean flows in South Puget Sound range from 40 to slightly over 17,000 m^3/s; and (3) these vary by a factor of two in many places due to seasonal changes in wind, freshwater flow, and tidal forcing. These model results confirm earlier observations of high volume transports in South Sound (Cokelet and others 1990). Although South Sound contains only a fraction of Puget Sound's overall volume of water, our model results indicate it is unexpectedly active with net transports comparable to that found in the much larger Main Basin off Seattle.

Introduction
Recent studies conducted by the Washington State Department of Ecology have revealed seasonally low oxygen levels in the South Puget Sound basin (Figure 1). To address this water quality concern and to evaluate nutrient sensitivity and loading, Ecology developed a project the South Puget Sound Area Synthesis Model, SPASM. The lowest oxygen levels recorded are even lower than distant upwelled Pacific Ocean water, which led us to the application of a coupled hydrodynamic/water quality model to study the fate and transport of reactive nitrogen as well as other water quality parameters for SPASM. In this paper, we are primarily concerned with the physical aspects of the processes leading to low oxygen.

The SPASM model uses the Environmental Fluid Dynamics Code, EFDC (Wu and others 1997), a 3-D hydrodynamic code based on the Princeton Ocean Model (POM). The SPASM model uses a grid of 1,906 horizontal curvilinear cells (Figure 2) and typically four layers in the vertical. We use the model to predict the mean flow both across transects where they are known, for the purpose comparison, and where they are unknown to understand more about South Sound mixing.

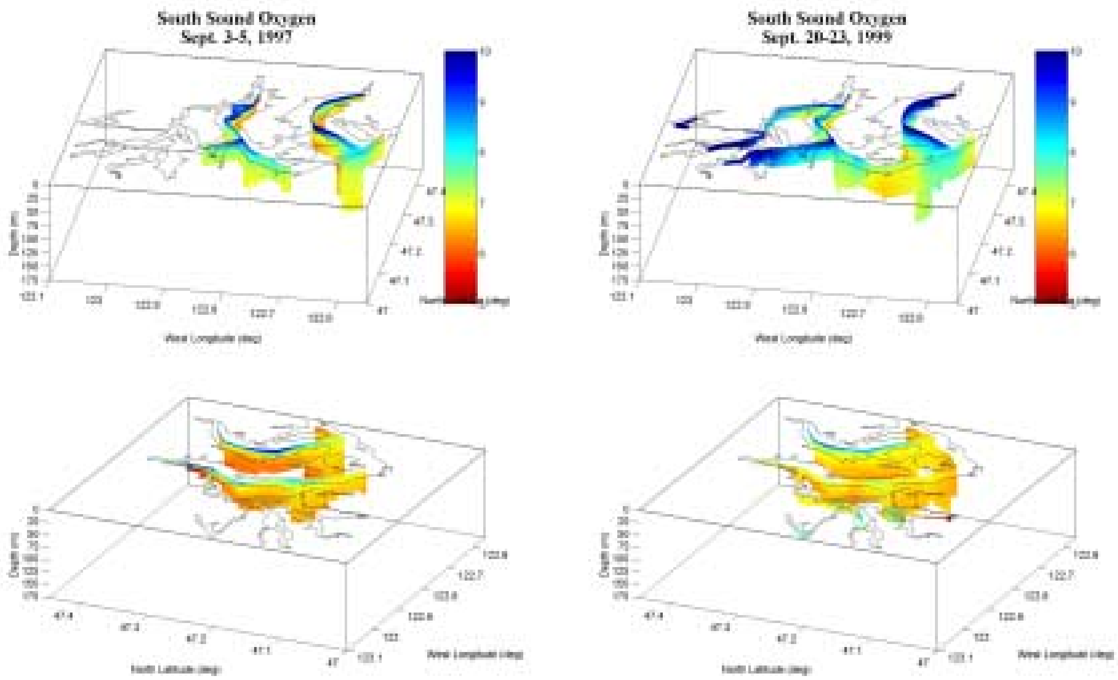

Figure 1 Low oxygen levels (red <= 6 mg/l, the WA standard for Class “A” water) in South Puget Sound during September 1997 and 1999.

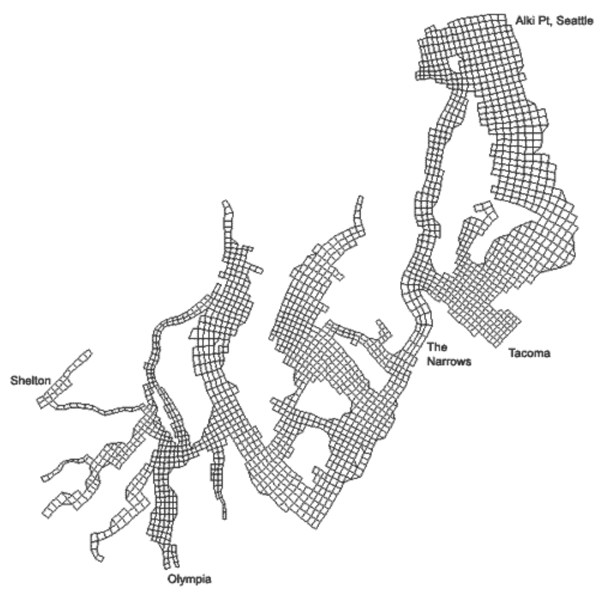

Figure 2 Curvilinear grid used in SPASM contains 1,906 cells of approximately 0.5 km on an edge.

The Budd Inlet Scientific Study (LOTT 1998) showed that the mean flow at the mouth of Budd Inlet calculated using a hydrodynamic model only doubled (200 to 400 m^3/s), despite six-fold variations in the freshwater inflow from the Deschutes River/Capitol Lake at the far-south terminus (from 5 m^3/s in summer to 32 m^3/s in winter). This implies a baseline net transport, which was largely attributed to tidal pumping as opposed to buoyancy forcing. The SPASM hydrodynamic model covers a larger area than the original Budd Inlet model, but at a lower spatial resolution.

On a larger scale, drift card releases suggest an H-like pattern in the mean flow where water from Totten Inlet exchanges with Pickering Passage, and water from Eld and Budd Inlets exchange through Dana Passage.

These observations of the complex and variable flows in this water-quality sensitive basin illustrate the need for a quantitative approach to estimate flows with adequate spatial and temporal resolution. We evaluate the SPASM hydrodynamic model in this paper.

Mean Flows Estimated by Tidal Prisms and Mass Balance

Without sufficient current measurements, or historically, mean flows were estimated from residence times that were calculated from tidal prisms or from hydrographic data and box models.

Southern Puget Sound has a volume at mean high water of 1.58×10^{10} m^3 (McLellan 1954). The mean barotropic tide inputs an intertidal volume of 1.66×10^9 m^3, implying an apparently short residence time of about 10 tidal cycles, or approximately five days by a tidal prism argument (Table 1A). The persistent stratification in the region, however, argues for evaluation of a residence time based on the tidally averaged baroclinic (internal or residual) exchange flow. Hydrographic data allow an estimation of this type of flushing under conditions occurring around the period when the observations are collected and using conservation of mass and salt in a box model. Evaluations of this mean flow produce much longer residence times, on the order of two months (Table 1B). Similar arguments can be made for individual embayments that compose the bulk of South Puget Sound (Table 1C).

Table 1. Annual average residence times derived by tidal prism and salt/mass balance (UW 1971; Duxbury and others 1972).

A. By tidal prism:

Volume ($10^8 m^3$)	Budd Inlet	South Puget Sound
@MHW	2.5	158.3
@MLLW	1.7	141.7
Intertidal	0.88	16.6
Residence Time (day)	1.4	4.9

B. By salt and mass balance (i.e., hydrographic data and a box model):

Inlet	Budd Inlet	South PS
Seaward transport (m^3/s)	1100	3300
Residence time (day)	2.4	56

C. Other SS Inlets by tidal prism:

Inlet	Residence time (day)
Carr	6.4
Case	3.9
Eld	1.4
Hammersley	0.9
Henderson	1.2
Pickering	1.9
Totten	1.2

Salt and mass balance residence times are quite sensitive to seasonal variability (Figure 3). Salt and mass balance residence times are more closely related to mean flow residence times than those derived by the tidal prism method that ignore the cancellation effect of the following tide. We conclude that the tidal prism method is a poor estimator of flushing throughout the South Puget Sound basin. The advantage of using a hydrodynamic model, such as SPASM, is that it can respond to specific seasonal and interannual-specific forcing, whereas salt and mass balances can only represent conditions for when those data are available.

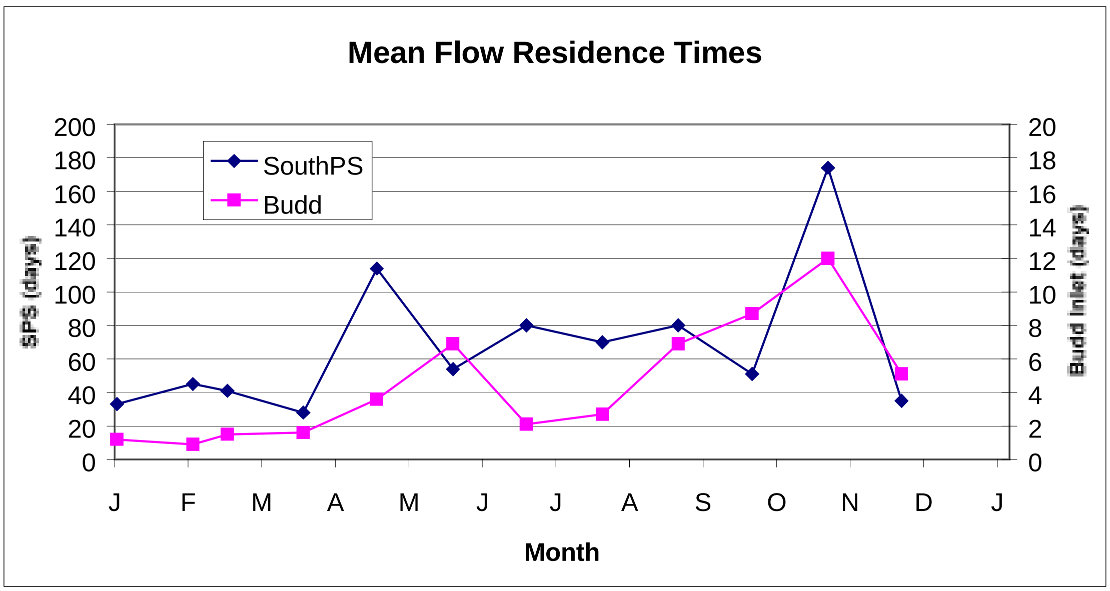

Figure 3 Seasonal variability derived from hydrographic data in Budd Inlet and South Puget Sound as a whole (UW, 1971; Duxbury et al., 1972).

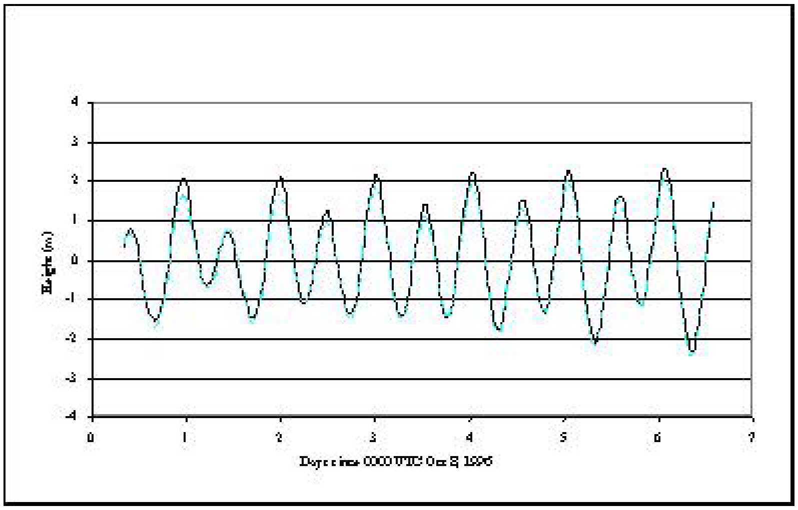

Figure 4 Tidal response for a week in the West Bay of south Budd Inlet. The model result is in blue and the field measurements (tide gauge) are in black.

SPASM Hydrodynamic Model

The EFDC hydrodynamic model solves the three-dimensional, vertically hydrostatic, free-surface, turbulent-averaged primitive equations of motion for a variable density fluid. Dynamically coupled transport equations for turbulent kinetic energy (TKE), turbulent length scale, salinity and temperature are also solved. The turbulence parameter equations implement the Mellor-Yamada level 2.5 turbulence closure scheme as modified by Galperin and others (1992). Time integration of the momentum and continuity equations uses a second-order, semi-implicit, three-time-level, leap frog-trapezoidal method, with an insertion of a two-time level trapezoidal step to suppress the mode generated by the three-level scheme. The barotropic and baroclinic modes are split with a method that is implicit in the horizontal for the barotropic, and in the vertical for the baroclinic. Advection is handled with an upwind difference technique described in Hamrick (1992a, 1992b, 1994). EFDC was selected because of these features and public availability. Our application of this code, the SPASM model, was calibrated with tide gauge data (Figure 4) and is forced with real temperature and salinity data at its open north boundary.

The calibration of the model for tides was accomplished by best fitting (least-squares) the response at ten internal tide gauge stations to forcing at the open north boundary (Figure 5).

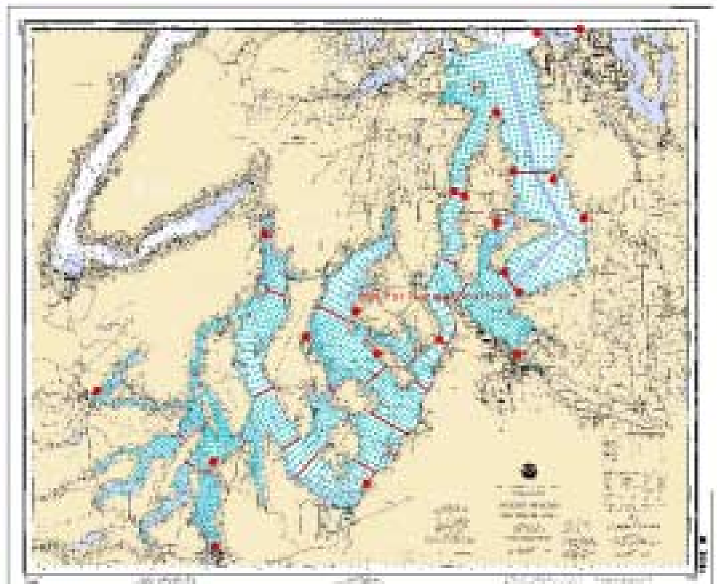

Figure 5 Chart with the ten tide gauge stations south of Tacoma Narrows used to calibrate SPASM (red dots). Chart also shows transects used to compute volume transports (red lines).

In the frequency domain transformation of sea-surface height time series from the model, there is a small advancement of phase lag, delta G, over the observed values from seaward to landward. This indicates that the model contains slightly too much friction (Table 2). A more complete evaluation of all the tidal constituents is available in Ecology's Phase I SPASM Project Report (in press).

Table 2. Observed and modeled amplitude (amp) and Greenwich phase angle (G) for M2 tide.

Station	Constituent	Obs. amp (m)	SPASM amp (m)	Delta amp (m)	Obs. G (deg)	SPASM G (deg)	Delta G
TN(6486)	M2	1.23	1.19	-0.03	21.4	17.5	-3.9
NQ(6828)	M2	1.34	1.36	-0.02	27.0	25.0	-2.0
BI(6969)	M2	1.46	1.47	0.00	29.9	31.2	1.3
OB(0178)	M2	1.49	1.38	-0.11	58.0	62.0	4.0

The first day in our model runs is set at 1 January 1996. The year of study for this report is 1 October 1996 to 1 October 1997. For this paper, historic winds from Seattle were applied globally to the model. We calculate the mean flow at each transect (Figure 5) by applying a 29-day 13-hour moving-window average on the velocity data output from the model in an external program (MATLAB).

Mean Flow Calculations

A buoyant patch of water at the surface would be moved into South Puget Sound with each flood tide, and be moved out of Puget Sound with each ebb tide plus a little bit. This steady progress seaward is the mean flow, in which we are most interested (Figure 6).

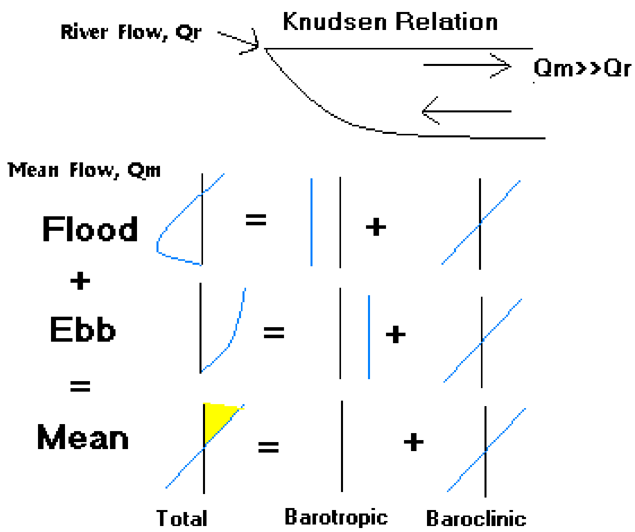

Figure 6 The mean flow concept. Qr is the freshwater input from a river and Qm is the tidally averaged mean flow.

South Puget Sound has a much more complicated geometry than the idealized one depicted in the Knudsen Relation of Figure 6. It is acted upon by winds and tides, as well as buoyancy forcing. Occasionally, this complex system becomes an inverse estuary, with greater freshwater discharge near its mouth, not its head (Figure 7). This is most likely due to the presence of snowmelt in the Nisqually River in late summer, as opposed to precipitation-fed, low-laying rivers and streams that feed the finger inlets (Budd, Eld, Totten and Hammersley) during the rest of the year.

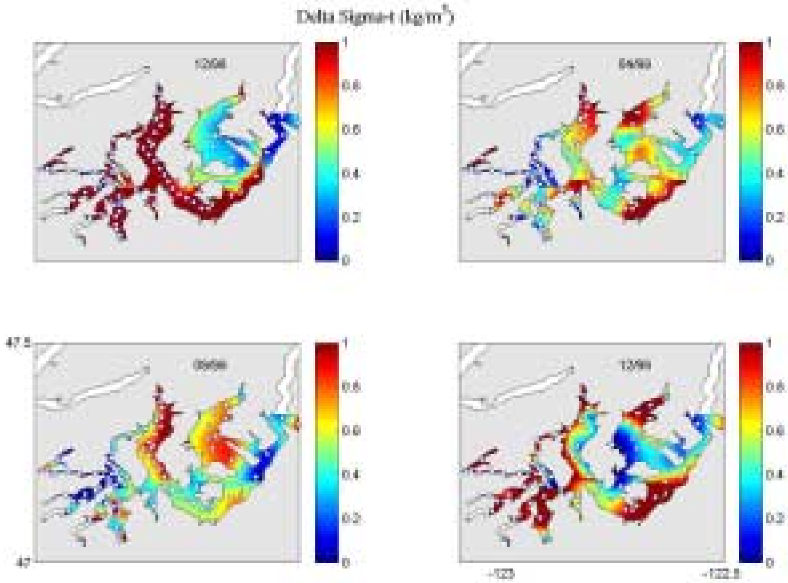

Figure 7 Normal buoyancy forcing with greater surface-to-bottom delta sigma-t near the landward head (April and December) of the system and inverse forcing with the greater stratification in Case Inlet seaward (September).

Model Results

At each transect we generated a cross-section of mean flow. The orientation was consistently looking seaward with red indicating flow away and blue indicating flow toward the observer (Figure 8).

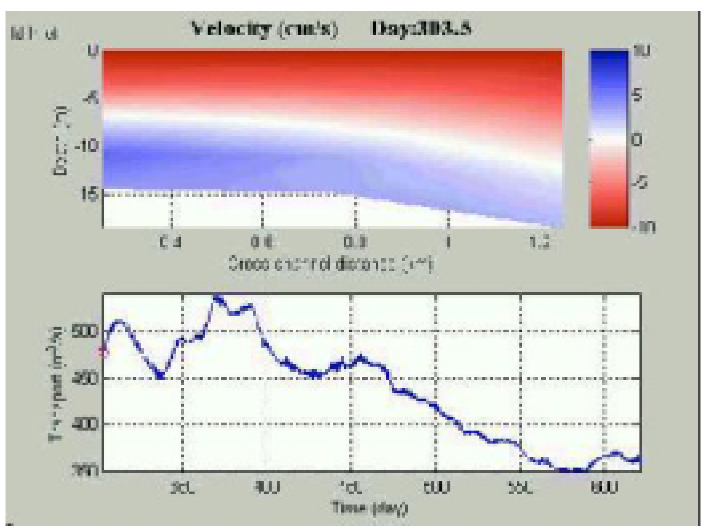

Figure 8 A snapshot of mean flow (top panel) and integrated transport (bottom panel) at the Budd Inlet north transect.

From these results, we computed flushing times (Table 3) and a map of net transport for late summer (Figure 9 and Table 4). The flushing times are much longer than those predicted by tidal prism calculations, sometimes by as much as a factor of ten. The late summer transports shown are an average, which does not depict the system's sensitivity to forcing mechanisms. Often the flow in one place is instantaneously diminished while the flow in another adjacent location is increased due to wind etc. This interdependence is not revealed in the mean.

Table 3. A comparison of residence times predicted by different methods. "N/A" means that values were not available.

Inlet	Budd	Eld	Totten	Hammersley	South Sound
Volume @ MHW(10^8 m^3)	2.52	1.59	2.13	1.48	158
Residence Time (day)					
By tidal prism	1.4	1.4	1.2	.9	5
By salt/mass balance	0.9-12	N/A	N/A	N/A	28-174
By SPASM model	6.5	8.4	4.0	46.3	124
SPASM Transport (m^3/s)	450	220	620	37	1480

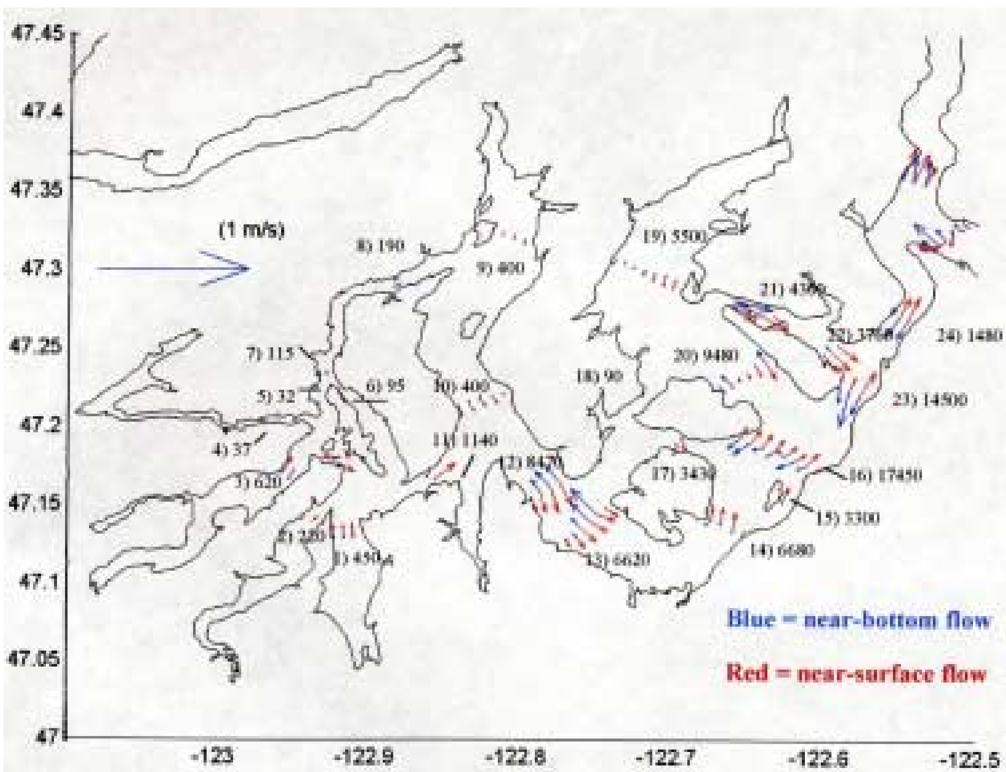

Figure 9 Volume transport (m3/s), indicated by numbers, and mean mean flow (m/s), indicated by arrows, for August 1997 derived with the SPASM model.

This paper estimates volume transports at many more transects than reported in previous literature. Volume transport at three transects previously computed, including the mouth of Budd Inlet (~400 m^3/s; LOTT, 1998), Devils Head (5,000 m^3/s; Cokelet and others 1990), and off Gordon Point (15,000 m^3/s; Cokelet and others 1990), agree fairly well with SPASM (Table 4). Despite its relatively coarse cell size, the transport in Budd Inlet agrees with the previous intensive study. SPASM and Cokelet *et al* (1990) both show that transports off Devils Head and Gordon Point are as high as levels seen in Puget Sound's Main Basin off Seattle (Cokelet *et al*, 1990). Despite differences of several thousand cubic meters per second, given the crudeness at which the transports are resolved, the agreement is considered satisfactory. This provides some measure of confidence in transports estimated at the other 21 transects. Nevertheless, these transports will require verification with current meter measurements in the future.

Table 4. A summary of August mean mean flows calculated with the SPASM model.

#	Transect	Transport (m^3/s)	#	Transect	Transport (m^3/s)
1	Budd	450	13	Treble Pt	6620
2	Eld	220	14	Cole Pt	6680
3	Totten	620	15	Cormorant Passage	3300
4	Hammersley	37	16	Gordon Pt	17450
5	SS Pickering	32	17	Balch Passage	3430
6	Peale	95	18	Pitt Passage	90
7	S Pickering	115	19	Carr	5500
8	N Pickering	190	20	McNeil to Fox	9480
9	N Case	400	21	N Hale Passage	4300
10	Case, Wilson Pt	400	22	S Hale Passage	3760
11	Dana Passage	1140	23	S Fox	14500
12	Devil's Hd	8470	24	Tacoma Narrows	1480

A 25th transect (unnumbered, but included in Fig. 9) north of Eld Inlet near Hope Island was not included because the mean flow across it was not monotonic. Evidence of a gyre or possibly twin gyres suggests that Hope Island significantly restricts the mean flow and could explain the H-divergence noted in the drift card study of the Budd Inlet study conducted in 1996-1997 (LOTT 1998). The model predicts a residence time in Oakland Bay that is particularly noteworthy since it is almost two orders of magnitude greater than that calculated by tidal prism.

Conclusions

Tidal prisms are a poor way to determine flushing times; they often underestimate residence times in southern Puget Sound by an order of magnitude. Estimates of transports in South Puget Sound derived using the SPASM model range from 40 to slightly over 17,000 m^3/s. Mean flows change by as much as factor of 2 due to seasonal changes in wind, freshwater flow, and tidal forcing. The mean flows around McNeil and Anderson Islands (#13, #14, and #17) interact in such a way as to suggest a meandering river. The model confirms the separation of Totten Inlet from Dana Passage via Hope Island, and the long flushing times in Oakland Bay near Shelton need to be verified with field measurements.

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